PALEOCEANOGRAPHY, VOL. 16, NO. 0, PAGES 1–6, MONTH 2001

Attenuation of millennial-scale events by bioturbation in marine sediments

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Abstract. The discovery of large, millennial-scale oscillations (1–10 kyr period) in climate records from ice cores and marine sediments in the North Atlantic has motivated the search to understand their cause and evaluate the geographic extent of this variability. One uncertainty in comparing marine geologic records of millennial-scale variability is the extent to which mixing of sediment by organisms at the seafloor (bioturbation) may attenuate millennial-scale events in the stratigraphic record. Evidence of attenuation of millennial variability can be found in cores with sedimentation rates in the range of 5–15 cm/kyr. Modeling the attenuation of a hypothetical input time series similar to GISP2 using a moderate level of mixing provides estimates of attenuation as a function of sedimentation rate. The amplitude of a 4 kyr duration event is reduced by 50% for sedimentation rates ~10 cm/kyr and reduced by 20% for sedimentation rates of 20 cm/kyr. Minimal attenuation (<5%) is achieved only when the sedimentation rate exceeds 50 cm/kyr for a 4 kyr duration event and 70 cm/kyr for a 2 kyr duration event. The intensity of mixing plays a role in determining how much attenuation occurs. The amplitude of a 4 kyr duration event in a 10 cm/kyr core is reduced by 75% under strong mixing or reduced by 25% under weak mixing. This study indicates that the original amplitude of Dansgaard-Oeschger (DO) millennial-scale events observed during the last glacial may be twice the observed amplitude for cores with sedimentation rates 10–20 cm/kyr that have experienced moderate bioturbation. Regional comparisons of the amplitude of millennial-scale variability will require cores with weak mixing or sedimentation rates exceeding 50 cm/kyr in order to avoid biased estimates of the amplitude of millennial-scale (4 kyr duration) variability.

1. Introduction

The discovery of millennial-scale climate variability in ice cores and ocean sediments has produced a vigorous effort to document and understand these large, fast, nonlinear mode switches in the climate system [see *Clark et al.*, 1999, and references therein]. Understanding these changes requires a geographically extensive suite of cores and proxy records and ultimately will require comparisons of the timing and amplitude of these events in different regions. Yet to date the record of millennial-scale variability is contradictory. Even within the same region, different cores provide different records of this variability, and it is difficult to summarize the amplitude of variability for a particular region, let alone how the variability changes geographically. Some of these differences may reflect differences in the original signal; however, other differences may be attributed to the fidelity with which the events are preserved by different proxy records. It is essential to understand how variations in sediment mixing by organisms at the seafloor (bioturbation) affect different proxy records of millennial-scale climate variability.

Mixing of sediment by organisms at the seafloor is a well-known process that has been examined in many different ways [*Berger and Heath*, 1968; *Boudreau*, 1994; *Guinasso and Schink*, 1975; *Officer and Lynch*, 1983; *Peng et al.*, 1979; *Trauth and Sarnthein*, 1997; *Wheatcroft*, 1990]. The attenuation of signals of different frequencies has also been examined [*Goreau*, 1977, 1980; *Schiffelbein*, 1984, 1985]. Mixing acts to homogenize adjacent sediment and reduces (smoothes) gradients in particle concentration. The effect of bioturbation is particularly obvious and can be quantified by an instantaneous sediment input (impulse event) such as a volcanic ash layer or the input of bomb-derived ^{137}Cs that is subsequently mixed upward and downward from its original position. Geochemical signals carried by particles, such as the oxygen isotope ratio contained in foraminifer shells, are also mixed according to both the gradient in the signal and the gradient in the carrier particles. The bioturbation process has been modeled using advection-diffusion models of varying complexity and by filtering in the time and frequency domains using filters constructed empirically from marine sediment profiles. On the basis of comparisons between modeled and observed profiles it is apparent that most sediments from oxygenated regions of the deep sea have experienced some mixing, that mixing rates vary over a broad range, and finally, that the attenuation that occurs is proportional to the original gradient in particle concentration. The last observation is important because it means that the faster the rate of change in concentration with respect to depth, the more an event will be smoothed by mixing. For an event of a given time duration the smoothing will be greater in more slowly accumulating sediment because the event is recorded over a shorter stratigraphic interval.

Most bioturbation models are able to simulate mixing reasonably well starting from an original concentration, yielding a mixed profile that matches well the geological data [*Peng et al.*, 1979]. The reverse process, unmixing the signal, is much more difficult because small variations and noise are easily amplified [*Bard et al.*, 1987]. The smoothing effect on glacial-interglacial timescales has been modeled using advection-diffusion models, leading to the common wisdom that sedimentation rates of 10 cm/kyr or more are needed to avoid significant signal attenuation. While this guideline is appropriate for cycles in the range of 100–20 kyr, the effect of bioturbation is theoretically greater for higher-frequency climate cycles [*Schiffelbein*, 1985].

Paper number 2000PA000530.

Table 1. Examples of Studies Documenting Millennial-Scale Variability in Marine Sediment Cores

Region	Core	Sedimentation Rate, cm/kyr	Reference
North Atlantic	Site 609	4	[*Bond et al.*, 1993]
Arabian Sea	70 KL	5	[*Sirocko et al.*, 1999]
North Atlantic	EW9209-1	5	[*Curry and Oppo*, 1997]
North Atlantic	V29-202	5–12	[*Oppo and Lehman*, 1995]
Arabian Sea	SO90-94KL	7	[*Schulz et al.*, 1998]
North Atlantic	CH69-K09	8	[*Labeyrie et al.*, 1999]
North Atlantic	V23-81	13	[*Bond et al.*, 1993]
North Atlantic	V29-204	13	[*Curry et al.*, 1999]
North Atlantic	PS2644	11	[*Voelker et al.*, 1998]
South Atlantic	RC11-83	23	[*Charles et al.*, 1996]
Bermuda Rise	MD95-2036	30	[*Sachs and Lehman*, 1999]
Cariaco Basin	Site 1002	50	[*Lin et al.*, 1997]
Santa Barbara Basin	Site 893	120	[*Behl and Kennett*, 1996]

No studies have specifically addressed the attenuation of millennial-scale variability other than to note the increase in attenuation on higher frequency [*Goreau*, 1977, 1980; *Schiffelbein*, 1984, 1985]. With the increasing emphasis on millennial and higher-frequency events, it is appropriate to examine the attenuation of these events in marine sediments with typical bioturbation rates. The goal is to determine an appropriate rule of thumb for the sedimentation rate needed to avoid attenuation of millennial-scale events. The approach taken is, first, to identify typical sedimentation rates where millennial-scale variability has been observed, second, to look for evidence of attenuation of millennial-scale events, and third, to examine model predictions of the attenuation of millennial-scale variability.

2. Cores That Preserve Millennial-Scale Variability

Recent papers describing millennial-scale variability in deep-sea sediments provide an indication of the sedimentation rates needed to preserve millennial-scale events well enough so that they can be detected (Table 1). Some of the original reports of millennial-scale variability utilized cores with sedimentation rates between 5 and 15 cm/kyr, and millennial variability has been observed in cores with sedimentation rates as low as 5 cm/kyr but rarely in cores with lower sedimentation rates. Millennial-scale variability is well resolved, with large amplitude in cores with sedimentation rates ~25 cm/kyr, for example, Bermuda Rise core MD95-2036 and South Atlantic core RC11-83. These sedimentation rates are not commonly found in the deep sea, where typical rates are ~1–5 cm/kyr. In Santa Barbara Basin, arguably the best developed record of millennial-scale variability outside the Atlantic, the sedimentation rate exceeds 100 cm/kyr. One can conclude that typical deep-sea sedimentation rates (1–5 cm/kyr) are not sufficient to preserve millennial-scale variability. Higher sedimentation rates are required.

These comparisons do not take into account the effect of variations in mixing rate, geographical variations in the original signal, or differences in the sampling interval, which determines the Nyquist frequency (the highest frequency that can be resolved). In addition to having a high sedimentation rate, Santa Barbara Basin, Cariaco Basin, and Arabian Sea sites also have very low rates of mixing because the oxygen content at the seafloor is very low. *Bond et al.* [1993] point out that V23-81 is not heavily bioturbated, and some of the other cores were presumably selected on the basis of the absence of bioturbation features. For a given sedimentation rate, short-duration events should be better preserved in cores where the mixing rates are low. Geographic variations in the intensity of millennial-scale variability could also explain the lack of variance observed in cores outside the North Atlantic. Variations in the sampling resolution could also explain some of the observed differences in amplitude. While these studies give a rough idea of what sedimentation rates are required to preserve millennial-scale events, a quantitative approach is needed to evaluate how much attenuation has occurred in the typical deep-sea environment.

3. Observed Attenuation

The attenuation caused by bioturbation can be observed by comparing time series in cores with different sedimentation rates. One such comparison can be made using the cores from *Bond et al.* [1993] in the North Atlantic. Bond et al. plot the time series of *N. pachyderma* abundance in two different cores from the same region together with the Greenland isotope record [*Bond et al.*, 1993, Figure 3]. The core with the lower sedimentation rate (609) has lower-amplitude DO cycles and is less similar to the Greenland record, relative to the high sedimentation rate core (V23-81). To make this comparison in the frequency domain, the time series were resampled at an even time step (500 years) for the interval from 10,000 to 60,000 years. The variance spectra were calculated from the Fourier transform of the autocovariance function [*Jenkins and Watts*, 1968], using a number of lags (13) equal to $N/8$ (selected to smooth the spectrum and reduce the uncertainty of the variance). The reduction in variance at higher frequency in the time series with the slower sedimentation rate (Site 609) is apparent (Figure 1). For events with a period longer than 10,000 years, the variance is about the same. At higher frequencies, the variance in the lower sedimentation rate core becomes progressively reduced. The attenuation at higher frequency is expected if bioturbation acts as a low-pass filter, as described by *Goreau* [1977] and *Schiffelbein* [1984]. The reduction in variance at higher frequencies can be attributed to the influence of bioturbation, which has a greater effect in more slowly accumulating sediments where each event occurs over a narrower depth interval. In the frequency domain the filter required to produce this smoothing would be a loss-pass filter, with a cutoff somewhere between the Milankovitch (1/20 kyr) and millennial (1/10 kyr) frequencies. This comparison is far from ideal. We assume the input to the seafloor at both sites was the same and contained variance similar to that observed in the ice core records. The two sites are from different locations and may have different surface conditions and input to the seafloor. Bioturbation rates and the depositional environment are not necessarily the same. Nevertheless, the comparison provides an empirical illustration of the attenuation that can be expected.

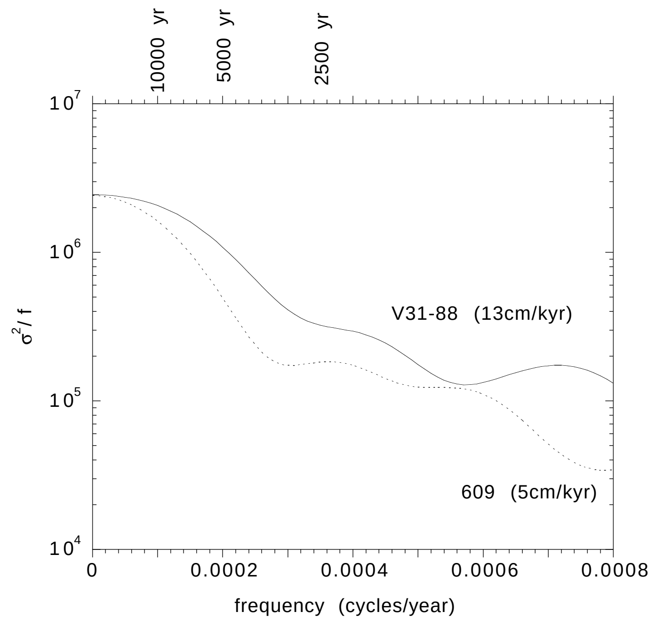

Figure 1. Spectral analysis of *N. pachyderma* abundance in two North Atlantic sediment cores for the interval 10,000–60,000 years B.P. (time series from *Bond et al.* [1993]). Core V31-88 has an average sedimentation rate of 13 cm/kyr, in contrast to Site 609, which has an average sedimentation rate of 5 cm/kyr. The original time series were interpolated at a 500 year time step to create a series of 100 points, and the low-resolution spectra were calculated from the Fourier transform of the autocovariance function using 13 lags.

Bond et al. [1993] point out that bioturbation is minimal in both of these cores. If this is the case, then this example can be considered as a minimal effect. Typical mixing rates would produce greater attenuation.

The carbonate record from core 70 KL in the Arabian Sea may provide another example of attenuation by bioturbation. The mean sedimentation rate is 4 cm/kyr, and the core was sampled every 1 cm (*Sirocko, et al.*, 1999). This sample interval (~250 years) is adequate to resolve both short and long DO cycles. Substantial millennial-scale variability is hypothesized because of the link between North Atlantic climate and the Asian SW monsoon. *Sirocko et al.* [1999] made extensive comparisons with Greenland Ice Sheet Project 2 (GISP2) and other records and correlated the longer-duration DO events, such as 8, 12, 16, and 17, but not the shorter-duration events, such as the Younger Dryas or events 4, 5, 6, or 11. There is thus some evidence that the longer-duration events are better preserved and more recognizable compared to the short-duration DO events. This evidence is not unequivocal because the original input signal to the Arabian Sea is unknown, but the better representation of the longer duration events at such a fine sample resolution (250 years) is consistent with the hypothesis that the short-duration millennial events have undergone substantial attenuation by bioturbation and are poorly preserved relative to longer-duration events.

4. Modeling the Attenuation

The attenuation of millennial-scale variability can be modeled using several different approaches. Advection-diffusion models [*Peng et al.*, 1979] have been used to model the diffusion that occurs in the seafloor mixed layer prior to sediment burial. These models are controlled by two parameters, the mixed layer thickness and the rate of diffusion, determined empirically. Depth series can also be modeled by convolving the original series with a filter constructed from observed ash layers or other profiles that show the distribution of an impulse event after mixing [*Hutson*, 1980; *Ruddiman et al.*, 1980]. More sophisticated models have also been proposed to consider the effect of organic flux on mixing rates [*Boudreau*, 1994; *Trauth and Sarnthein*, 1997] and the effect of particle-size-dependent mixing [*Wheatcroft*, 1992]. The convolution approach is used here because it is computationally simple and avoids the need to estimate values for unknown parameters, such as mixed layer depth, rate of diffusion, porosity, carbon flux, particle size, or sediment density. The influence of these parameters is incorporated in the convolution approach into the ash filters. We used three different filters determined by *Ruddiman et al.* [1980] to span the range of bioturbation intensity observed in the deep sea on the basis of observed ash profiles. They labeled these filters strong, intermediate, and weak with regard to mixing intensity. The first step in convolution is to identify a hypothetical input time series. The first-order question is, To what extent would the DO variability indicated by the ice core records would be attenuated in the deep sea? Therefore the GISP2 isotope record was used as an input time series, scaled to an amplitude of 1.5‰, sampled at a time step of 100 years, and expressed as a deep-sea sediment foraminifer oxygen isotope record with constant carrier concentration and sedimentation rate. Next, the time series was converted to a depth series using different sedimentation rates (100, 30, 20, 10, and 5 cm/kyr) to produce five different depth series. The ash filters were constructed by smoothing and then scaling the observed ash profiles from *Ruddiman et al.* [1980] in the depth domain so that their sum equals unity. The isotope depth series were convolved with the ash filters to produce the convolved (mixed) sediment series. The convolution process smoothes the original time series using the weights of the ash filter and can be envisioned as an *n*-point moving average, where the weights of the smoothing filter are the values from the ash filter. For example, a depth series containing an impulse event (one value of 1, all other values

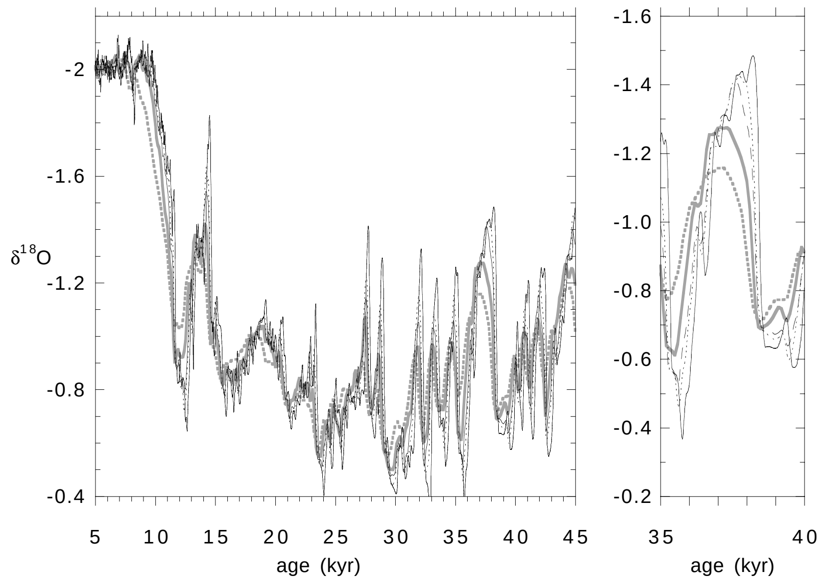

Figure 2. Time series of hypothetical oxygen isotope variation in deep-sea sediments with different sedimentation rates (solid line, 100 cm/kyr; short-dashed line, 30 cm/kyr; long-dashed line, 20 cm/kyr; thick gray line, 10 cm/kyr; gray dashed line, 5 cm/kyr). The hypothetical input time series used was the Greenland Ice Sheet Project 2 oxygen isotope time series, scaled to 1.5‰ amplitude, and expressed as a deep-sea sediment depth series with constant sedimentation rate and carrier abundance. Five different input series (corresponding to 100, 30, 20, 10, 5 cm/kyr sedimentation rates) were smoothed using the moderate ash layer filter from *Ruddiman et al.* [1980] to simulate the effect of bioturbation in the deep sea.

zero) when convolved with the ash filter produces the original ash profile. The five convolved depth series were converted back to time series to produce the results shown in Figures 2 and 3.

The result of moderate mixing of the hypothetical GISP2 input is shown for sedimentation rates ranging from 5 to 100 cm/kyr (Figure 2). The input time series cannot be distinguished from the 100 cm/kyr series and is not shown. Visually, there is little

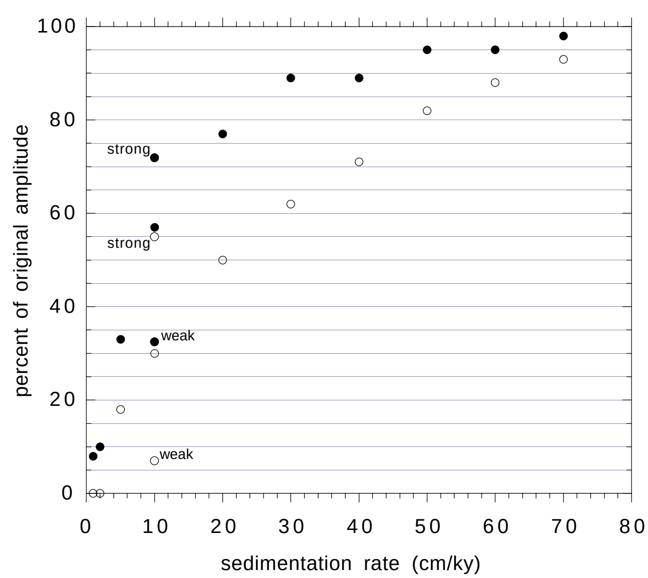

Figure 3. Attenuation of millennial-scale events using the moderate mixing filter from *Ruddiman et al.* [1980], expressed as a percentage of the original amplitude for a long- (solid circles) and a short-duration (open circles) millennial oscillation. Attenuation was measured as the amplitude across the transition from Dansgaard-Oeschger (DO) event 8 to the minimum between events 7 and 8 (a long-duration event, period of 4 kyr) and DO event 4 to the 3-4 minimum (a short-duration event, period of 2 kyr) in time series with different sedimentation rates (four of the series are shown in Figure 2). The range of attenuation caused by weak and strong mixing filters are indicated for the 10 cm/kyr case.

difference between the100 (thin solid line), 30 (short-dashed line), and 20 (long-dashed line) cm/kyr records except for the highest-frequency events, which have undergone some attenuation. The location of the peaks is shifted very little. At 10 cm/kyr (thick gray line) the attenuation and the shifting of peaks is obvious and is greatest for the short-duration events and less for the long-duration events. At 5 cm/kyr (gray dashed line) the attenuation is substantial, the events are displaced in time, and the rate of change is reduced.

To quantify the relationship between sedimentation rate and attenuation, the amplitude of change was measured between DO event 4 and the minimum between 3 and 4 (a short-duration DO event, period of 2 kyr) and between event 8 and the minimum between 7 and 8 (a long-duration DO event, period of 4 kyr). Amplitude is expressed as a percentage of the original amplitude (Figure 3). As expected, the attenuation of the short-duration event is largest. For sedimentation rates of 10 cm/kyr the reduction in amplitude is severe, ~70%. Only when sedimentation rates exceed 70 cm/kyr does the attenuation decrease below the level of the noise in most paleoproxy measurements (~5%). For the longer-duration event, sedimentation rates of 10 cm/kyr preserve 50% of the original signal, and sedimentation rates of 50 cm/kyr preserve 95% of the original signal. This is a crude way to estimate the attenuation because it is specific to events of 2 and 4 kyr duration; however, it does demonstrate the extreme sensitivity of attenuation to event duration in the millennial frequency band. For the cores listed in Table 1 with sedimentation rates in the 10–20 cm/kyr range that have experienced moderate bioturbation, the original amplitude was probably a factor of 2 higher. Any comparison of the relative amplitude of glacial-interglacial versus millennial-scale variability in these cores is probably biased, with only the glacial-interglacial amplitude faithfully preserved.

Although outside the scope of this paper, it is important to note that another effect of bioturbation is to displace the location of events relative to their original position [*Hutson*, 1980]. Some displacement occurs even with an instantaneous input. *Ruddiman et al.* [1980] found that the weighted mean of the particle distribution closely approximates the original location of the input (the location of the peak after mixing may not be the same location as the weighted mean). Mixing acts to move particles from regions of higher to lower concentration. For the case of paleoproxies such as alkenones and foraminifer isotope concentrations, whose concentration may be varying in different ways with respect to depth or which may be mixed differently owing to size-dependent particle mixing, it is unlikely that the original stratigraphic position of millennial-scale events in cores that have undergone some mixing would faithfully be preserved for each proxy. At millennial scale one might also expect the age associated with a particular carrier, such as a foraminifer species, to be displaced relative to other proxies. Like the attenuation of amplitude, the displacement of peaks would be greatest where changes in concentration are large and minimal for proxies whose concentration remains constant.

5. Variations in Mixing Rate

The examples above consider only an average mixing rate and do not consider variations in mixing. Yet there is abundant evidence that mixing rates in the deep sea vary over a wide range [*Guinasso and Schink*, 1975; *Schiffelbein*, 1985; *Trauth and Sarnthein*, 1997]. For a given sedimentation rate some cores will be more mixed and some will be less mixed because of differences in mixing rate. Mixing rates can vary geographically and also vary in time. There is also some indication that the carbon flux to the seafloor may also affect the mixing rate [*Trauth and Sarnthein*, 1997]. We considered the effect of varying mixing rate by convolving the same profiles using the weak and strong filters from *Ruddiman et al.* [1980]. For the 10 cm/kyr sedimentation rate case the minimum (weak filter) and maximum attenuation (strong filter) are shown for the 2 and 4 kyr event as lower and upper bounds (Figure 3). The range between minimum and maximum attenuation is 40%, indicating that mixing rate has a large influence on how much of the signal is preserved. In the best case, a core with a 10 cm/kyr sedimentation rate that has undergone only weak mixing will preserve 70% of the original 4 kyr event amplitude. For most deep-sea records the mixing rate and its variation through time are not known. Some measure of mixing intensity, for a particular time interval in a particular core, would be useful in reconstructing the true amplitude of an event. The presence of ash layers or other instantaneous events provides a straightforward although time-consuming way to determine the mixing filter. If the mixing rate could be extrapolated to other sections of the core based on a relationship with sediment type, carbon concentration, or other characteristics, a quantitative estimate of attenuation could be made throughout the core.

6. Conclusions

Millennial-scale variability has been observed in cores with sedimentation rates >5 cm/kyr. Cores with sedimentation rates in the range of 5–15 cm/kyr reveal millennial-scale variability; however, there is some evidence that the amplitude has been attenuated. A survey of some recent results indicates that millennial-scale variability is best preserved in cores with sedimentation rates ~25 cm/kyr and above. These comparisons are not ideal because the cores were sampled at different resolutions and are found in different depositional environments and because the original input to the seafloor is unknown. A hypothetical input signal similar to that found in the ice cores was bioturbated by convolving the input signal with a filter derived from observed ash layers in order to find out whether this signal would be preserved in the deep sea. Substantial attenuation occurs when sedimentation rates are in the 5–15 cm/kyr range. Modeling the attenuation of millennial-scale events (4 and 2 kyr duration) with moderate bioturbation indicates that sedimentation rates in excess of 50–70 cm/kyr are required to keep attenuation under 5%. Some cores, with weak bioturbation, probably achieve this fidelity if the sedimentation rate is above 25 cm/kyr. Variations in the rate of mixing have a large effect on attenuation. For sedimentation rates in the 10 cm/kyr range, weakly mixed sediments are attenuated by 30%, whereas strongly mixed sediments are attenuated by 70%. Some measure of mixing intensity, for a particular stratigraphic horizon in a particular core, would be useful in determining the original amplitude of a millennial-scale event and avoiding biased estimates of millennial-scale variability. Regarding the comparison of the amplitude of millennial-scale versus glacial-interglacial change observed in marine sediments, the results of this study indicate that while the amplitude of glacial-interglacial change is faithfully preserved, the amplitude of millennial-scale events has probably been reduced by half for cores with sedimentation rates 10–20 cm/kyr that have experienced moderate mixing at the seafloor.

Acknowledgments. Will Berelson and Walt Dean provided helpful reviews, John Crusius provided FORTRAN code and advice that allowed comparison of the advection-diffusion and convolution approaches, and Jerry McManus and Katsumi Matsumoto provided valuable comments on an earlier draft.

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(Received April 12, 2000;
revised January 18, 2001;
accepted March 7, 2001.)